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Relative life cycle economic analysis of stand-alone solar PV and fossil fuel powered systems in Bangladesh with regard to load demand and market controlling factors

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ABSTRACT

In this paper, relative life cycle economic analysis (LCEA) of stand-alone solar PV modules is performed with respect to portable fossil fuel driven power sources to test their commercial prospects in remote regions of Bangladesh which do not have a direct access to grid supply. Overall life time expenditures related to the power projects are analyzed and compared with the help of net present worth (NPW) theory. The influence of market controlling factors like government subsidies, excess inflation over the general trend, and price hike are established with case study of medium-scale petrol–diesel generators (0.8–10 kW) and solar photovoltaic modules (100 Wp). It is found that the cost effectiveness of conventional or 'green' power driven sources depends on kW rating of generators and daily demand on customer-end in the context of a developing country like Bangladesh. The demand coverage which would determine the commercial viability of renewable and non-renewable sources is calculated considering pragmatic power rating of generators available in the local market. This study is intended to assist planning of financial matters with regard to installing small to medium scale renewable projects in remote localities of Bangladesh.

Contents

1. Introduction

A country's economic growth and social development are directly dependent on the efficiency of its energy sector. Being a

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developing country located in South Asia, Bangladesh is currently facing considerable problems in the power generation industry. Generation of electricity through power plants is heavily dependent on natural gas in this nation [1]. But, there is a significant deficit between supply and demand for this resource which could reach up to 1000 million cubic feet per day by the end of 2020 [2]. In the absence of a reliable supply for crude oil, coal and other conventional fossil fuels, the country has not been able to compensate for the existing power deficit, ultimately leading to a poor living standard for its people and a persistent energy crisis hindering its rural electrification projects. The forecasted gap between generation and demand for electricity can reach a peak value of 2000 MW during summer months of 2012, when extra supplies will be required to power pump-driven irrigation systems in rural areas [3]. When it comes to utilizing renewable resources, potential for installing hydro-power plants is limited to the south-eastern sections of the country in the absence of suitable ecological setting and natural reservoirs in other parts. A few initiatives have been launched to install stand-alone and grid-connected wind turbines in the 20 kW–1 MW range [4] but their prospects are uncertain because of seasonal intermittency of wind forces and long distance between major grid lines and potential windy sites [5]. Under such circumstances, solar power is considered to be the most promising source for alternative energy in Bangladesh with available mean solar irradiation reaching a peak value of up to 5 kW h/m^2 in summer months [6]. Fuel powered (diesel and petrol) generators are widely employed in localities of Bangladesh with limited or no access to grid-generated electricity. The equipment cost relevant to these commercial generators is significantly less than solar PV modules with the same power rating [7]. Because of this reason, the economic feasibility of mass deployment of solar panels is often put into question citing business risks [8]. But the fact of the matter is that, solar PV systems do not incur recurring fuel expenditure like petrol generators. The government and the Ministry of Power of Bangladesh have also undertaken various steps to subsidize solar panels and offered tax-exemptions to make them commercially competitive. The robust nature of stand-alone solar modules ensures a lower frequency of maintenance and servicing operations which ultimately leads to reduced operational costs. With concerns regarding global warming rising over the last decade, solar PV systems can contribute by saving 500 kg of CO_2 per year for a 100 Wp solar home system [6], which verifies their eco-friendly nature. Therefore, conventional appraisal techniques to measure cost-effectiveness will not be suitable to judge the different cost structures of fuel generators and solar systems. A more reliable method which incorporates individual cost components incurring over a systems entire life span and measures future expenses at their present worth is termed as Life Cycle Economic Analysis (LCEA) [9]. In this paper, LCEA method is applied to evaluate life-cycle expenditures related to medium-scale renewable and traditional (1–10 kW) power projects. Net present worth (NPW) theory is employed to explain the influence of market controlling factors (discounting, inflation, price hike) on the unit cost of electricity produced by power generators. The break-even points indicating the relative outlay performance of solar and generator cost curves are determined for pragmatic daily loads for rural stand-alone systems (0.4–14 kW h). The correlation between kW rating of generators and customer-end demand is established for different power ratings. This study is intended as an assisting tool for economic management of proposed renewable projects to be built in Bangladesh.

The paper is structured as follows. In Section 2, background is provided to justify the use of life cycle analysis for portable systems. Section 3 documents the theory of LCEA with the help of net present value theory. The existence of break-even points is established by analyzing the cost performance of solar modules and fuel generators in Sections 4 and 5. Sections 6–8 derive the effect of market controlling factors on the unit cost of electricity and explain their significance for the Bangladeshi economy.

2. Literature review

LCEA (Life Cycle Economic Analysis) calculates the spending on a service delivered over the total life span of a project. This is important because the initial investment outflow does not always reflect the true expenses related to a delivered service. Operation, maintenance and several other outlays are also considered in LCEA to estimate the true economic burden of a product [7]. Hence, LCEA can be more useful than conventional approaches to assess the economic feasibility and long run performance of a solar PV system. In the context of Bangladesh, solar PV units usually incur greater initial investment cost than petrol or diesel generators. For this reason, fuel driven generators may seem like a more attractive option than the solar PV units if only initial investment expenditure is taken into account. But in the long run, the overall per unit energy production cost for fuel driven generators might not necessarily be better than the per unit electricity cost for solar PV modules. For this reason the life cycle approach has gained popularity among the researchers and been followed in a number of research projects related to energy production [10–16]. Agustin and Lopez have studied the economic and environmental impact of solar PV technology in Spain using life cycle analysis. They calculated profitability of PV installation, net present value (NPV) and payback period for different energy tariff and inflation rates [10]. Byrne et al. have shown that in rural Western China, off-grid stand-alone renewable technologies like small PV, wind and wind-PV hybrid units are more cost-effective than conventional generators to improve the rural energy scenario. Using 531 different household samples, they have combined LCEA and Geographic Information System (GIS) while evaluating the potential for renewable energy projects [11]. Bhuiyan et al. find solar PV to be a more cost-effective option than diesel or petrol generators for rural Bangladesh. According to their analysis, life cycle cost per unit energy for grids 1 km away from a village is much higher than that of a comparable solar PV system [7]. Iskander and Scerri performed cost evaluation and sensitivity analysis of the first solar PV system installed in Madagascar. They considered the lifetime for a solar PV system to be 20 years and found that it is reasonable to use this data in economic evaluation of PV systems [12]. Hiranvarodom employed life cycle technique to assess the economic feasibility of a 2170 Wp (capacity) PV system installed in Rajamangala University of Technology, Thanyaburi district, Pathumthani province of Thailand [13]. Oparaku unveils the tremendous prospect of solar PV systems as the source of low power electrical energy in rural communities of Nigeria using the same analysis. He studied life cycle costs of diesel and gasoline powered generators and performed sensitivity analysis using module coast, diesel price and grid extension variations [14]. Qoaider and Steinbrecht performed LCEA to compare the electricity generation cost of PV systems and diesel generators set in a remote agricultural community of Southern Egypt. They found the per unit electricity cost of a diesel generator three times higher than that of PV system [15]. Kannan et al. provided a comprehensive performance analysis of a 2.7 kW p grid connected PV system in Singapore combining elements of life cycle assessment theory with other techniques. They showed that PV systems are environmentally more reliable than conventional gas or oil fired steam turbines [9]. Kolhe et al. compared the life cycle spending between solar PV systems and diesel powered systems in India. They found that PV

systems are economically the cheapest option at an energy demand of up to 10 kW h per day. With favorable economic conditions (e.g. decreased PV system price, increased diesel cost), the cost-effectiveness of PV systems can be sustained for even higher energy demands [16]. So, LCEA should be an ideal tool to verify the relative cost performance of portable power systems for rural daily loads applicable for Bangladesh.

3. Economy of life cycle economic analysis (LCEA)

Life cycle cost analysis is a statistical tool which assigns weighted values to initial and possible future expenses related to a project and provides a cost assessment appropriate for the present economy. It is versatile in the sense that it can be applied at any level of a design process (for the entire project or for individual components) [17]. In case of a power generation site, it covers the total disbursement in three individual stages: initial capital phase, maintenance phase and decommissioning phase. At the onset of the project, spending on construction, equipment, installing and manpower is included in initial capital cost, measured in the present economy. The outlay necessary for keeping the system operational is included in the maintenance phase and it contains regular fuel expenses and costs incurred during maintenance. These outflows occur on a regular basis and the total period of analysis is also included in the assessment. The third and final phase (for decommissioning) covers the spending related with termination of the project and safe disposal of equipments in service. All these expenses are accounted to their present worth (depending on existing and projected inflation and price trend) and summed up to provide the total life cycle cost (LCC) of the project. The final step of the process will be converting the overall outlay incurred over a project lifetime into unit-cost per kW h (load) of energy, which will be employed to make comparative assessments between different power supplies [9].

3.1. Effective present value (EPV)

As life cycle analysis has to include future expenses for the system under study, which may or may not happen on a recurring basis, effective or net present value (EPV) of the components has to be calculated to make a meaningful evaluation of future costs in the present economy. For this reason, prospective future disbursements due to maintenance and replacement are discounted to their equivalent level in the existing economy and the present worth of the spending is calculated accounting inflation and market trends.

3.2. Net system cost

The net system cost for a power generation sector incorporates three components which cover the price tags attached with expenses incurred during the three phases considered by life cycle economic analysis. Examples of these components are provided in the following sections.

3.2.1. Initial capital cost

The spending needed for purchasing equipments is included in the study as capital expenditure. It covers cost of PV module parts including dc batteries, solar panels, inverter blocks, installation and wiring for a photovoltaic system. If import levies and transport duties are applicable, as when modules have to transferred from commercial centers to remote regions, they will termed as capital expenditure. In case of diesel or petrol generator driven stand-alone systems, capital cost comprises paying for generator body, prime mover, circuit breaker, installation, change-over and miscellaneous equipment expenses.

3.2.2. Recurring or regular costs

These expenses occur in a periodic fashion over every year the service is in operation and are primarily related with maintenance of hardware, site supervision and overall system management. A regular schedule has to maintained for servicing the generator parts during which it must be ensured that the generator is able to support rated load without consuming extra fuel. The batteries, inverters and assembly of a solar PV system require inspection after intervals of every 3 months.

3.2.3. Replacement or non-recurring costs

One-time or non-recurring expenses may take place on an irregular basis. If certain parts of the power supply are damaged by an accident or components start to underperform, they may have to substituted with new equipments, thus increasing the overhead for the system. To ensure quality of performance, major components like batteries for a PV system have to be replaced after 5 or 10 years of service. These outflows are included in the category of single-payment costs.

3.3. Economic criteria

3.3.1. Effective period of analysis

It is standard practice in life cycle analysis to consider the lifetime of the supply with a longer life span as the period of analysis. In case of PV modules available in the local market built with modern silicon technology, their mean lifetime is expected to reach 20 years whereas a 6.2 kW petrol generator gives efficient service for 5 years in average [7]. So, if LCC analysis is employed to compare the cost-effectiveness of petrol generators and solar home systems, the service time of the solar module (20 years) will be taken as the analysis period.

3.3.2. Excess inflation and discount rate

In economic terms, if the capital investment of a power project were diverted to a savings scheme, it would have been able to accrue interest over the system's lifetime. The price of system components also escalates over time depending on the state of the economy. Discount rate (d) considers these circumstances and gives proper weightage to expenses so as to make a capital owner indifferent to whether he received a share of profit now or a greater reimbursement at some time in the future [17]. If other forms of compensation like subsidies from the government are available for environment friendly initiatives, it would also affect this discount rate. Excess inflation (i) is an indicator of general trend in cost escalation over the projected average inflation rate. It would affect all system elements in a uniform fashion. In this paper, these two discounting factors are applied to future expenses to make an estimate of their effective present worth.

3.4. Life cycle cost (LCC) and unit electricity cost (UC)

The total net present worth of regular and replacement expenses has to be estimated in the final step of life cycle cost analysis. In this process, the future spending is discounted by a factor determined by excess inflation and discount rates. As the first initiative of price discounting, rate of inflation is excluded from calculation and discount rate only considers the time-value of money. For a single non-recurring replacement cost C_{rep}, which is expected to be paid after a period N years, effective present worth (PW) is estimated by

$$PW_{rep.o} = C_{rep} \times P_{ro} = C_{rep} \times \left(\frac{1}{1+d}\right)^{N}, \tag{1}$$

where d and P_{ro} stand for independent discount rate and present worth factor for replacement costs, respectively. Similarly, if the

amount of a recurring payment is C_{rec}, discounted (inflation free) present worth (PW) will be given by

$$PW_{rec.o} = C_{rec} \times P_{ao} = C_{rec} \times \left[\frac{(1+d)^N - 1}{d \times (1+d)^N}\right], \tag{2}$$

where P_{ao} stands for simplified present-worth factor for recurring expenses.

To make a complete assessment of market controlling factors, when rate of inflation (i) is also taken into account [18], Eq. (1) looks like

$$PW_{rep} = Cr \times P_r = C_{rep} \times \left(\frac{1+i}{1+d}\right)^N, \tag{3}$$

and the modified Eq. (2) for regular or recurring payments (including the influence of i) takes the form of

$$PW_{rec} = C_{rec} \times P_a = C_{rec} \times \left[\left(\frac{1+i}{1+d}\right)\left(\left|\frac{1+i}{1+d}\right|^N - 1\right) \Big/ \left(\frac{1+i}{1+d} - 1\right)\right]. \tag{4}$$

The present-worth factor for regular costs (P_a) is also called the annualization factor (AF), as it represents the number of years which can effectively account for the entire analysis period. For example, in the absence of inflation and with a 10% discount rate, annualization factor for a 20 year analysis period of a solar module is given by 8.51. So, the definitions of present-worth factor for one-time (replacement) costs (P_r) and annualization factor for recurring costs (P_a) are given by

$$P_r = \left(\frac{1+i}{1+d}\right)^N \quad \text{and} \tag{5}$$

$$P_a = AF = \frac{\left(\frac{1+i}{1+d}\right)\left(\left|\frac{1+i}{1+d}\right|^N - 1\right)}{\frac{1+i}{1+d} - 1}, \quad \text{respectively}. \tag{6}$$

After deriving the life cycle costs of individual spending components of a power supply and calculating their present worths with Eqs. (3) and (4), the sum of all discounted estimates gives the grand life cycle cost (LCC) of the supply. Annualized (per year) life cycle cost (ALC) and unit electricity cost (UC, spending per kW h of energy) are calculated from overall life cycle cost using annualization factors (AF, in years) and rating of daily load demand (LD, residing in the 0.4–14 kW h range) using the following expressions:

$$ALC = \frac{LCC}{AF}, \tag{7}$$

$$UC = \frac{ALC}{LD \times 365}. \tag{8}$$

Samples of life cycle calculation are provided in the following section which will further illustrate the theory.

4. Life cycle analysis of fossil fuel sources and stand-alone solar PV module

If we need to make a comparative assessment of performances achieved by rival power suppliers, the first step would involve determining the average daily load demand that the concerned systems have to serve. A typical stand-alone solar PV system employed in the rural communities of Bangladesh would serve a daily load varying from 100 W to 3.5 kW with system back-up of 4 h. So, the daily load range selected for this study covers a range between 0.4 and 14 kW h. When this load will be served by 1–10 kW fuel driven traditional generators, their daily operating hours would start from 2 h but may reach a peak of 15 h for full-load condition. This range and running hours are applicable for remote rural localities of Bangladesh served by stand-alone and mobile power supplies. For the same demand coverage, annualized life cycle cost and unit production expenses are calculated for portable solar modules, medium-scale petrol generators (1.5, 3–4, 5 and 7 kW) and commercially available diesel generators (1, 3–5, 6 and 10 kW). Generator data are collected from a leading local manufacturer and supplier of fuel generators (Walton International) who has provided information about equipment figures, fuel consumption rate, operating hours, parts and maintenance for their Power-Craft-700 and ZET-1000 Series models [19]. This section will compare unit cost calculations and determine the range of loads for which a stand-alone solar system would offer lucrative economic returns over a portable generator. The design and service criteria which make a medium-scale petrol or diesel generator more cost-efficient than its solar counterpart will also be established.

To produce an example of relative life cycle cost estimation in the selected range, 18 loads are selected with 200 W intervals in the 100–3500 W domain. A system back-up of up to 4 h makes the maximum demand limit for these stand-alone systems to be 14 kW h. Life cycle costs are measured in this situation as the load is served by PV modules and selected generators. Effects of cost escalation are included with a 10% discount rate and excess inflation is considered to be absent. It would mean that an annualization factor of 8.5136 (following Eq. (6)) will be appropriate for discounting the expenses if the photovoltaic modules are expected to last for 20 years. Rating for three major components of a PV module is determined by the instantaneous load demands. The first component is a dc battery for charge storing (typically 48 V for small loads) and it is standard practice to make the size of the battery double of the required ampere-hours. To allow provision for peripheral losses, the second component (solar panels) is set to have a rating which is 25% higher than the nominal demand (in Watt–hour). There will also be random losses involved with power conversion in the back-end inverter, the third PV module element. So, the inverter rating is fixated at a value which is 110% of the solar panel size (in Watts). For example, for a 100 W (0.4 kW h) load, the panel and the inverter will have 0.125 and 0.138 kW ratings, respectively whereas the 48 V battery will need to give a service of 16.67 A h. Table 1 provides sample calculations measuring rating of PV module elements for representative dominant loads in the 0.4–14 kW h range. Corresponding price data are collected from the data sheet provided by a national supplier (Watt-sun Solar Trackers) [20]. In the next step, life cycle (LC) cost analysis of a stand-alone solar PV module with a 2.38 kW Solar Panel for 7.6 kW h daily load is detailed in Table 2. In an identical manner, LCC is tabulated for the other demand values in

Table 1
Rating of parts of a solar PV system for representative dominant loads in the 0.4–14 kW h range.

Daily demand (Watt–hour)	PV system parts	Rating (in Amp–hour or Watt)
0.1 kW*4 h=400	48 V battery rating	(400 W h*2)/48 V=16.67 A h
	Panel size	(400 W h*1.25)/4 h=0.125 kW
	Size of inverter	125 W*1.1=.1375 kW
1.9 kW*4 h=7600	48 V battery rating	(7600 W h*2)/48 V=316.67 A h
	Panel size	(7600 W h*1.25)/4 h=2.375 kW
	Size of inverter	2375 W*1.1=2.6125 kW
2.7 kW*4 h=10,800	48 V battery rating	(10,800 W h*2)/48 V=450 A h
	Panel size	(10,800 Wh*1.25)/4 h=3.375 kW
	Size of inverter	3375 W*1.1=3.7125 kW
3.5 kW*4 h=14,000	48 V battery rating	(14,000 W h*2)/48 V=583.33 A h
	Panel size	(14,000 W h*1.25)/4 h=4.375 kW
	Size of inverter	4375 W*1.1=4.812 kW

Table 2
Life cycle (LC) cost analysis of a stand-alone solar PV module with a 2.38 kW solar panel serving a 7.6 kW h daily load (BDT=Bangladeshi Taka, USD=US dollar, 75 BDT=1 USD).

Capital breakdown	BDT/Watt	BDT	USD
(a) Cost for solar panel	200	475,000	6333.3
(b) Inverter cost	70	182,875	2438.3
(c) Installation (cables)	50	118,750	1583.3
(d) Solar mounting	20	47,500	633.33
(e) Cost of battery	200	63,333	844.44
(f) Charge controller	20	47,500	633.33
(g) Miscellaneous	20	47,500	633.33
(1) Capital cost, total (=a+b+c+d+e+f+g)		827,333	11,819.09
(2) Cost of fuel	(No fuel required)	0.00	0.00
(3) RMC[a]	Annual maintenance, Ca	5000	71.43
	Annualization factor, Pa (from Eq. (6))	8.51	8.51
	Life cycle maintenance cost (LCMC) (=Ca*Pa)	42,550	607.86
(4) NRC[b]	Battery replacement (BR, in 10 years time)	63,333	844.44
	General component replacement, GR (in 10 years time)	5000	71.43
	Sub total, Cr (=BR+GR)	68333	911.11
	Present worth factor, Pr (10 years time) (from Eq. (5))	0.39	0.39
	Life cycle replacement cost (LCRC) (=Pr*Cr)	26,650	355.33
LCC[c] for 20 years (=1+2+3+4)		1,051,658	14,022

[a] Recurring maintenance cost.
[b] Non-recurring cost (replacement cost).
[c] Life cycle cost.

Table 3
Comparison of UC (unit cost, derived from annualized LCC) between stand-alone PV, 4 kW petrol gen. and 6 kW diesel gen.

Daily demand (DL)	0.4 kW h			3.2 kW h		
Resource	Solar PV	Petrol gen.	Diesel gen.	Solar PV	Petrol gen.	Diesel Gen.
LCC, 20 years (BDT)	97,508	128,495	345,401	468,567	476,384	482,382
ALCC (BDT)	11,458	15,099	40,588	55,061	55,979	56,684
Unit cost (BDT)	78.48	103.42	278	47.141	47.928	48.531
Unit cost (USD)	1.046	1.379	3.71	0.629	0.639	0.647
Daily demand (DL)	7.6 kW h			14 kW h		
LCC, 20 years (BDT)	1,051,658	1,023,066	697,638	1,899,791	1,818,241	1,049,875
ALCC (BDT)	123,579	120,219	81,979	223,242	213,659	123,370
Unit cost (BDT)	44.549	43.338	29.552	43.687	41.812	22.838
Unit cost (USD)	0.594	0.578	0.394	0.582	0.557	0.305

the selected range (0.4 kW h–14 kW h) in case of 100 Wp PV modules and 1–10 kW petrol–diesel generators. This provides the platform to estimate annualized LC spending using 8.5136 as the annualization factor for a service time of 20 years. Finally, Eq. (8) measures unit production cost for the power supplies and Table 3 presents a scenario which compares the unit production cost of a stand-alone PV unit, a 4 kW petrol generator and a 6 kW diesel machine for loads from all parts of the spectrum.

5. Existence of break-even points on cost curves

The first reading of Table 3 suggests that for a low demand for electricity, unit cost of a photovoltaic module is much cheaper than fuel powered generators, but as daily demand increases, machines run on fossil fuel may become more cost-effective. For example, at the lowest limit of the load spectrum (0.4 kW h), unit expense for the PV system is only USD1.05/ kW h (USD=US dollar). On the other hand, spending for every kW h of electricity generated by petrol and diesel machines are 132% and 356% of the solar standard, respectively. In sharp contrast, as the load is raised to 3.2 kW h, the three unit outlays become more balanced and remain within 1.5% of the USD0.63/kW h mark. As the daily demand approaches the 10 kW h mark, the diesel generator achieves the highest cost-efficiency and the solar module along with the petrol generator offers a slightly more expensive alternative. This indicates the existence of a break-even point on the unit cost versus demand curves generated by the three systems under observation [20]. To quantify this point, we compare the unit outflow of a stand-alone solar PV system, 1–10 kW diesel generators and 1.5–7 kW petrol generators servicing the 0.4–14 kW h demand range in Figs. 1 and 2. Fig. 1 manifests that, in case of widely employed diesel generator ranges (3–6 kW) and PV systems, the break-even points (where the curves for the PV module and the diesel unit cross each other) are confined within the 2–3.3 kW h domain. For 10 kW and 1 kW diesel machines, this point gets more spread, reaching 5.9 and 0.85 kW h limits. A sample implication of this phenomenon is that above the 3.3 kW h demand range a 6 kW diesel generator becomes more cost-effective than a comparable PV system. As shown by Fig. 2, for a 1.5 and a 3 kW petrol generator units, cost of the solar system is always lower in the entire demand range, so the break-even points are non-existent in these cases. For a larger (7 kW) petrol generator, the break-even point has already moved to the left of the frame at 3.6 kW h. In this case, the PV module will be the cheaper alternative in the 0.4–3.6 kW h range. More detailed analysis is necessary to establish the petrol generator ratings (in kW) for which the load break-even point settles within 3–10 kW h, a typical coverage for stand-alone daily rural loads.

To attain this design information, petrol generators are tested with small increments in ratings (0.2 kW) varying from 3.2 to

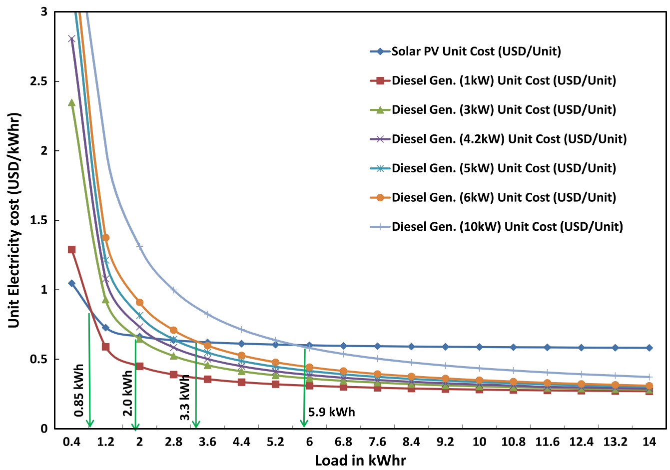

Fig. 1. Relative performance of diesel generator and solar PV unit in terms of unit production cost (USD/kW h).

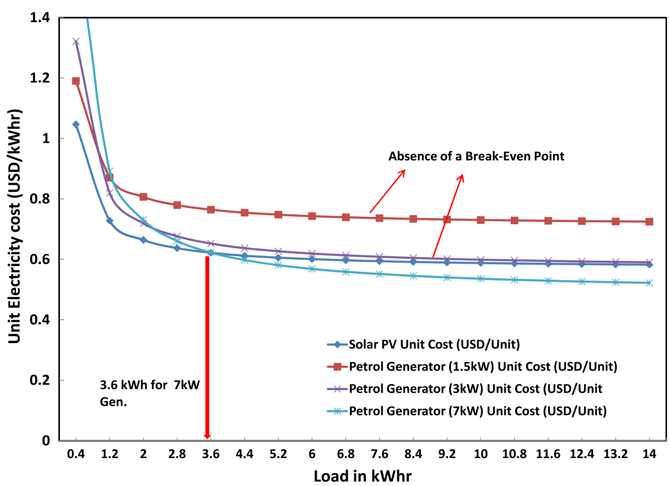

Fig. 2. Comparative cost performance of petrol generators (1.5–7 kW) and a solar PV system.

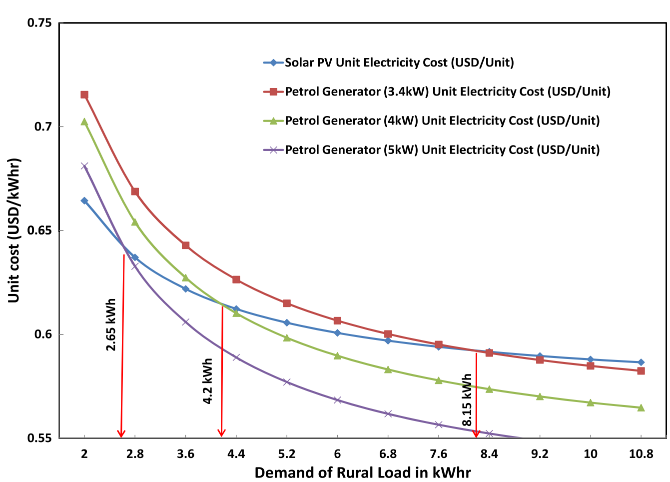

Fig. 3. Leftward movement of break-even points with generator power rating (3.4–5 kW).

5 kW and the results are plotted in Fig. 3. Sharp movement of the break-even point from right to left (8.2–2.7 kW h) becomes evident in this analysis as petrol generator rating is raised to 5 kW. The results proclaim that we need higher power rating from conventional generators for them to be economically

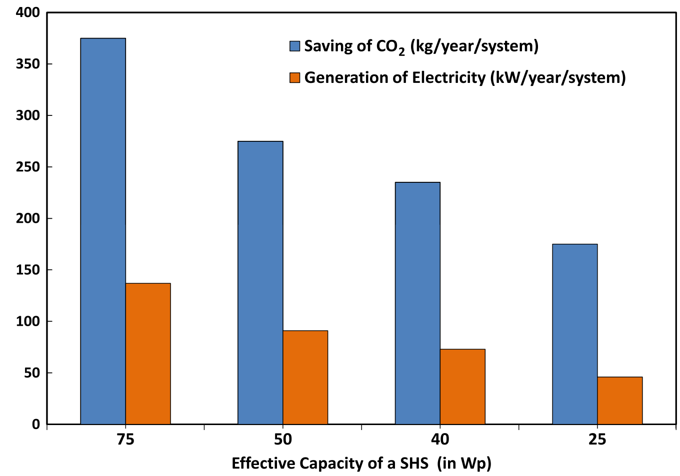

Fig. 4. Comparison between production of electricity and saving on CO_2 emission by a solar home system.

competitive with PV systems. But this would also lead to higher emission of green-house gases and increased fuel consumption rate despite the fact that a 5 kW petrol generator will save money in the 2.65–14 kW h range. A solar PV is supported by statistical proofs which states that it reduces green-house gas (CO_2, CH_4) emission to the atmosphere in significant amounts [6]. Fig. 4 compares the amount of electricity produced and the volume of CO_2 saved by a stand-alone solar home system (SHS) with commercial power ratings on a yearly basis over a period of 20 years. This graph can be considered as a measuring standard to quantify the carbon-output effect of power sources and it indicates that if petrol or diesel generators were used in place of a 75 Wp solar system an extra 375 kg of CO_2 would have been added to the atmosphere every year. As we move to 50–25 Wp system, carbon saving is also reduced but still, it remains on the positive side of 180 kg per year for a single installment.

6. Influence of economic discounting and inflation

As was mentioned in the section discussing the theory of life cycle economic analysis, different market controlling factors influence the discounting of spending which occurs sometime in the future. The first element to be considered in the assessment of market factors is the discount rate (*d*), which was defined in Section 3. The volatility of the global economy can lead to a certain degree of uncertainty in all financial parameters. Therefore, to establish a standard rate to be employed for life cycle analysis, a standard practice will be to follow the rate determined by the country's ministry of energy [17]. One have to keep in mind that the economic criteria to evaluate a solar PV module differ from those of conventional small power projects in the sense that a number of extraneous economic factors make selective contributions to these units. The government of Bangladesh has given special initiatives in the form of subsidies and tax-cuts to promote the use of 'green' energy resources (like solar home systems) in remote or suburban areas. So, if we initiate the analysis with a nominal discount rate of 10% for all power systems, *d* for petrol–diesel using generators will remain unchanged, but discount rate for solar modules may fluctuate to a certain extent. This phenomenon will affect the annualization factor (*Pa*) and the present worth factor (*Pr*) and the hence, the cost estimation of recurring or non-recurring disbursements. In the context of a heavily subsidized developing country like Bangladesh, the range of variation for *d* is selected 3–18% [18]. Considering the market structure and the

Table 4
Influence of discount rate and excess inflation on annualization (*Pa*) and present worth factors (*Pr*).

Discount rate, *d* (excess inflation absent)	Annualization factor for recurring cost, *Pa* (year of analysis = 20)	Present worth factor for non-recurring cost (Pr), replacement	
		After 10 years	After 5 years
0.03	14.8775	0.7441	0.8626
0.1	8.5136	0.3855	0.6209
0.12	7.4694	0.322	0.5674
0.18	5.3528	0.1911	0.4372
Excess inflation, *i* (discount rate = 10%)	Annualization factor for recurring cost, Pa (year of analysis = 20)	Present worth factor for non-recurring cost (Pr), replacement	
		After 10 years	After 5 years
0.0	8.5136	0.3855	0.6209
0.03	10.764	0.5181	0.7198
0.05	12.7177	0.6280	0.7925
0.07	15.1511	0.7584	0.8709

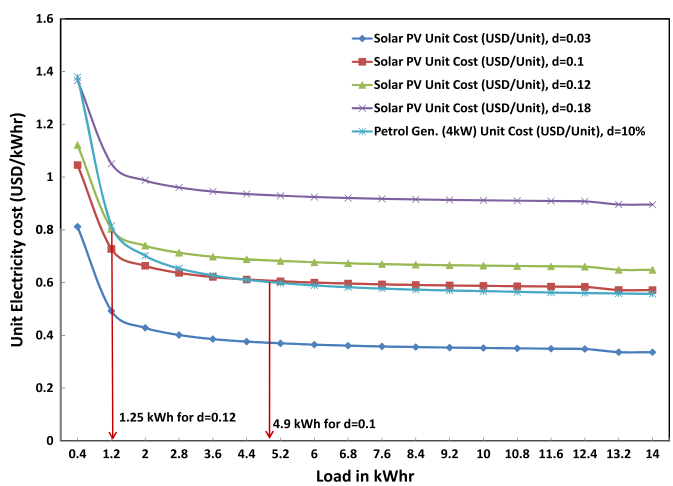

Fig. 5. Effect of variable discount rate (3–18%) on daily stand-alone loads (0.4–14 kW h).

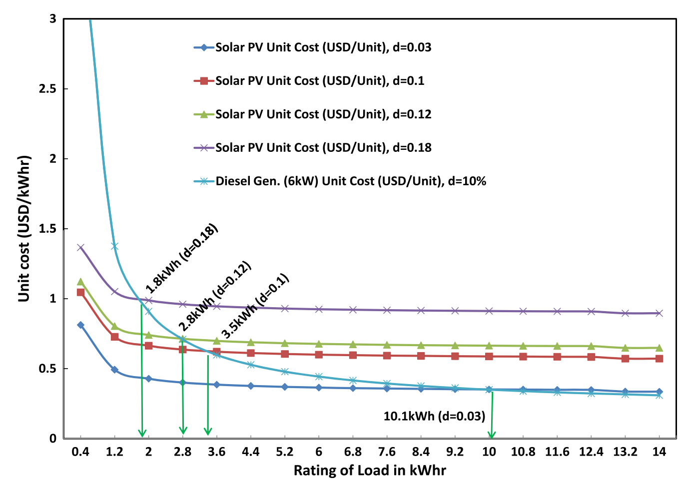

Fig. 6. Influence of subsidizing (discounting) on diesel generator (6 kW) and solar PV module.

trend in general inflation over the last decade [21], the excess escalation factor (*i*) may be taken as 3–7%. Only time-value of money will also have to be considered in this situation without including the effect of inflation existing in the market. Table 4 shows the influence of discount rate and excess inflation on annualization (*Pa*) and present worth factors (*Pr*) needed for LCC analysis. These values are obtained from Eqs. (5) and (6) and it may be noted that the study period for recurring costs is taken as 20 years (mean life time of a PV module) whereas the present worth factor for one-time costs will depend on whether a specific element is being replaced after 5 or 10 years. As expected, the two discounting rates have opposing influences on the derived factors. Although, the rate of discount remains stable for fuel-driven machines but improves for rural solar projects depending on economic initiatives provided by the government, excess inflation rate affects the calculation of production cost of all power supplies in a uniform manner [22]. The next step of relative comparison would involve performing the solar PV calculations of Tables 2 and 3 once again, but now with variable discounting rates for 3–10 kW diesel machines and 1.5–7 kW petrol generators. The range for *d* and *i* are included as 3–18% and 0–7%, respectively, to analyze the consequence of fluctuating market controlling factors on the aforementioned demand range of 1–14 kW h, representative of daily usage of electricity in rural communities of Bangladesh depending on stand-alone power projects.

7. Effect of inflation and subsidizing factors on break-even points

To establish the modified break-even points on the solar and petrol-driven systems, a 10% discount rate (*d*) is initially applied on a 4 kW Walton petrol generator. Accounting for the influence of government subsidizing, the discount rate for Watt-sun solar modules is considered in a number of steps (3, 10–12 and 18%). The unit production cost is plotted against the demand range of both systems in Fig. 5. If the two curves cross each other at a certain demand point, it would mean that there is a significant difference in the cost-effectiveness of the supplies. The absence of the break-even point, on the other hand, would indicate the superiority of one particular supply system for that load range. Fig. 5 suggests that solar PV and petrol generators can be compared only if the discount rates are in the vicinity of the 10% mark. In this range, the break-even point moves to the left from 4.9 to 1.25 kW h as the PV discount rate rises from 10 to 12%. For a 3% discount rate, the solar module is always less expensive than the 4 kW generator and when $d = 18\%$, the situation is reversed. In the meanwhile, the unit production cost remains confined in the range of 0.4–1.2USD/kW h. Break-even points exist for all possible values for the discount rate (3–18%) when the cost curves are plotted for a 6 kW diesel generator and the PV units in Fig. 6. When the discount rate is 3% the unit cost of the PV unit is cheaper (0.4–0.7USD/kW h) than the

diesel generator up to a load of 10.1 kW h. Above that limit, the cost performance of the two systems follow a similar pattern. If the rate is raised to 10%, the break-even point is lowered down to 3.5 kW h implying that the solar supply provides better cost performance below this demand. At higher discount rates of 12% and 18%, the break-even points is lowered even further to 2.8 and 1.8 kW h, respectively, making the diesel generator more cost efficient for most of the permissible load combinations. So the results suggest that the economic performance of a portable power supply depends on effective discount rate applicable for the current economy to a great extent. To evaluate the influence of excess inflation on spending trends, price escalation (i factor) is varied from 0 to 7% for a typical discount limit. In the meanwhile, the unit outlay of solar PV units is compared with a 6 kW diesel generator in Fig. 7 and a 4 kW petrol system in Fig. 8 for the identified daily demand range. Fig. 7 indicates that raising the inflation rate reduces the life cycle costs for both PV units and fuel generators. In the absence of excess inflation, the point of intersection stands at 3.3 kW h. A higher rate of inflation shifts down both set of curves, but the solar costs move down by a greater amount. As a result, the cross-point moves to the right at 5.1 and 6.8 kW h when i stands at 5 and 7%, respectively. When the 4 kW petrol generator stats are plotted in Fig. 8, its unit production cost only changes by a small margin (USD0.05/kW h) for a variable i factor. As a consequence, the two set of curves cross each other (at 4.2 kW h) only in the absence of excess inflation. For other combinations, the solar PV units provide the better option in the 0.4–14 kW h range. The results suggest opposing influences of discount rate and rate on inflation on life cycle economic analysis of stand-alone power supply systems.

8. Fuel price hike and cost performance

In recent times, uncertain political climate in the petroleum producing regions of the earth has led to wide fluctuations in international fuel prices. Although, the petroleum import sector of Bangladesh is heavily subsidized, fuel prices in this country have seen sharp changes over the last 5 years. So, how the varying fuel prices may affect the existing break-even points should be scrutinized in relation to the spending pattern of the power systems we have discussed. As the PV module depends on a renewable resource to replenish its fuel supply, its cost performance will not be affected when petrol or diesel prices are considered as variables. Over the course of 2 years running from ’06 to ’08, gasoline prices have changed as far as 75–146 dollars a barrel in the international market. The pricing of petrol or diesel in the local commerce is highly sensitive to this international oil trade situation and may vary randomly over a short period of time. These effects are illustrated on the unit electricity cost versus daily demand curves plotted in Figs. 9 and 10. The current price of diesel and petrol per liter in the

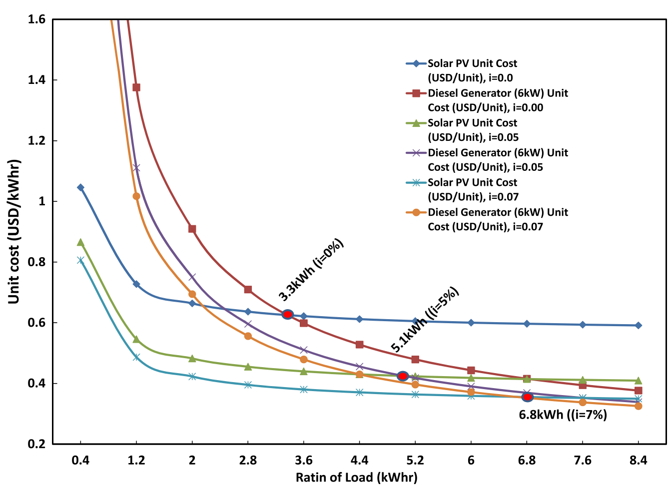

Fig. 7. Prominent movement of break-even point with excess inflation (0–7%) influencing diesel and solar units.

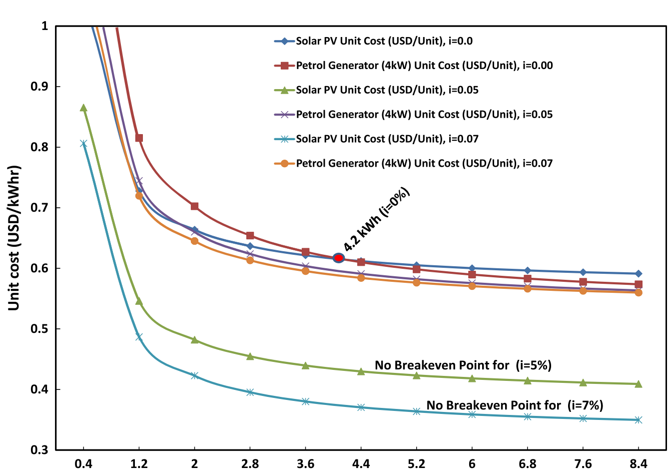

Fig. 8. Absence of break-even points in certain cases when inflation affects solar PV and petrol generators.

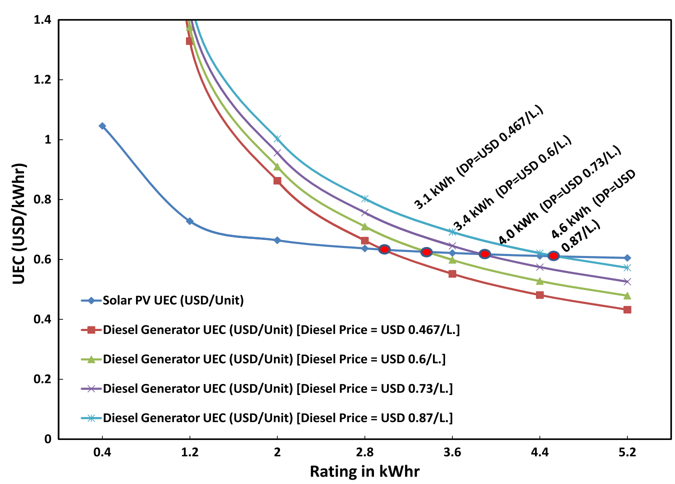

Fig. 9. Effect of increase in diesel price on relative cost curves generated by conventional generators and solar PV modules.

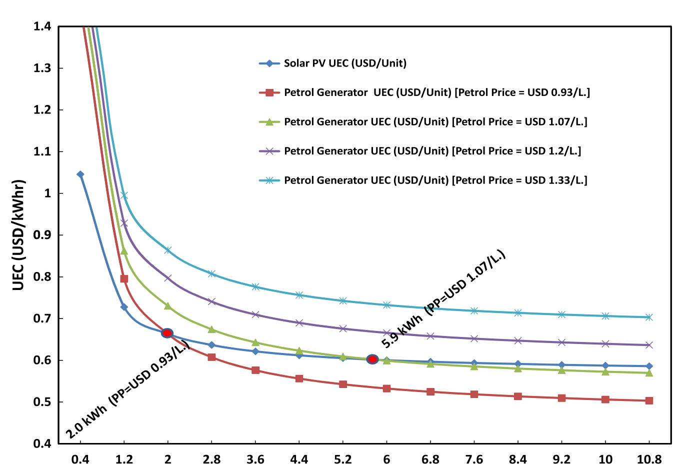

Fig. 10. Sharp variation in cost-effectiveness with petrol price hike.

Bangladeshi market are BDT 80 (USD 1.07) and BDT 45 (USD 0.6), respectively. Analyzing the market trend, diesel price is analyzed with a range of USD0.46–0.87 per liter and for every liter of petrol the range is taken as USD0.93–1.33. Fig. 9 proves that the influence of diesel price on the unit production spending is not very prominent. As the diesel cost is raised from BDT 35 (USD0.46) to BDT 65 (USD0.87), unit electricity cost remains in the proximity of 0.65USD/kW h and the intersection-point between solar PV and diesel generator curves progresses from a 3.1 kW h to a 4.6 kW h load. Because of the higher price tag of petrol, a petrol price hike, as shown in Fig. 10, will result in sharper movement. When the petrol price is BDT 70-80 (USD 0.93-1.07) per liter, the break-even point shifts from 2 kW h and 5.9 kW h, and when the tag is USD1.2 or more, the stand-alone PV module proves cheaper for the entire load range. So, any change in the local fuel prices should be considered as an influential factor in life cycle economic analysis.

9. Conclusions

The objective of this paper is to prove the multi-variable dependency of unit production outflow from portable or stand-alone power projects employed in the South Asian country of Bangladesh. To establish the relative cost-effectiveness of medium scale (up to 10 kW) fuel generators and solar PV modules, life cycle economic analysis (LCEA) is employed to calculate the weighted cost of a service discounted to the present economy. When a typical stand-alone load range is investigated for a rural community, it is found that the unit electricity cost of generator or photovoltaic units depend on daily demands and rated power output (kW) of the machines. When compared with medium size (3–5 kW) generators, solar modules offer a lower per unit spending for lower demands (from 0.4 up to 8 kW h) and petrol–diesel generators provide financial gains for larger loads (reaching 14 kW h). Net present value theory is employed to investigate the current worth of future expenses and the influence of market controlling factors like rate of discount, excess inflation and commercial oil prices. Considering all these points, unit disbursement for electricity is found to vary between USD0.35 and 2 for every kilowatt-hour of load. This paper establishes break-even points on the relative cost curves generated by renewable or traditional power sources and identifies their movement with variable economic factors. It also determines the demand range which would return higher economic returns for a medium size PV module when compared to fossil-fuel driven sources in the context of a developing country like Bangladesh.

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